

FABRICATION AND CHARACTERIZATION OF 6H-SiC SWITCHING DEVICES

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Abstract

Various 6H-SiC switches, including Schottky diodes, p⁺n diodes and thyristors have been fabricated and characterized using optical and electrical triggering. Mesa etching is accomplished by electron cyclotron resonant reactive ion etching using CF₄ and O₂ mixture, with a high etch rate of 80 nm/min and an excellent surface morphology. The optical triggering by 266 nm laser light yields a near 100% switching efficiency in Pt and Au 6H-SiC Schottky diode switches, and a 75% switching efficiency in p⁺n 6H-SiC diode switches. A breakdown field of more than 1x10⁶ V/cm is obtained in p⁺n diode. Operation of SiC thyristor is demonstrated. A relatively long turn-on time of 170 ns is believed to be due to a long base region and a short carrier lifetime in 6H-SiC.

I. Introduction

The recent progress in SiC crystal growth and material processing has stimulated a great interest in SiC electronics technology[1-5]. The most important driving force in the research of SiC technology is the need for high-power, high-temperature optical and microelectronic devices resistant to radiation damage. The wide bandgap and high breakdown field of SiC makes it an ideal choice. Presently, almost all power devices are made from silicon. High power switching devices are widely used in various types of power systems, such as high-power pulsed lasers, high-power microwave systems, etc. In many cases, not only a high blocking voltage is required, but also a high operating temperature is desired. Both Si and GaAs switches apparently can not meet such requirements. Typical operating temperatures of Si power devices are below 200°C. With the progress in doping control, high purity 6H-SiC layers with carrier concentration less than 5x10¹⁵/cm³ are available now. This could mean a blocking voltage of about 3000 V. A number of successful SiC devices has been demonstrated. A high temperature rectifier made from 6H-SiC is demonstrated to have reverse breakdown voltage of 1400 V at room temperature and 710 V at 623 K [6]. A switching speed in the 10-20 ns range at 623 K has been observed in a 6H-SiC pn junction diode[4]. A Pt/6H-SiC Schottky diode has been shown to have 400 V reverse breakdown voltage and 10 ns turn-off time [7]. Admittance spectroscopy has been used to study deep traps that play an important role in SiC devices[8]. MOSFET and MESFET devices, as well as ultraviolet photodetectors have also been demonstrated [5,9].

However, there is few reports on the study of switching characteristics of SiC switches for pulsed power application. In this paper, we report on the fabrication and characterization of various 6H-SiC switches, including Schottky diodes, p⁺n diodes and thyristors. We report the first optical triggering of 6H-SiC Schottky and p⁺n diode switches with near 100% switching efficiency. The properties of 6H-SiC thyristor operation are discussed.

II. Device Fabrication

Three different sample structures were grown by Cree Research Inc. on N-type 6H-SiC substrates of 1" diameter and (0001) Si terminated surface. The parameters of each sample structure are summarized in table I. Briefly, a low doped n-type 6H-SiC layer was grown on n⁺ substrate for Schottky diode fabrication. A p⁺-type 6H-SiC layer and a low doped n-type 6H-SiC layer were grown on n⁺ substrate for p⁺n diode fabrication. The thyristor consists of a p-type 6H-SiC layer grown on n⁺ substrate followed by a thick n⁺ 6H-SiC base layer and a thin p⁺ 6H-SiC emitter layer.

Mesa etching is a critical step in the fabrication of SiC pn diodes and thyristors. Dry etching using fluorinated gases (such as CF₄, NF₃, et al.) have been used to etch SiC[4,5]. However, low etch rates (<30 nm/min) and rough surfaces have been reported using CF₄ gas [10]. Our samples would require a mesa etch depth of more than 2 μm. In the first etching experiment, one 6H-SiC sample was etched in a conventional parallel plate reactive ion etching (RIE) system using CF₄ + O₂ mixture with 250 W rf power and 200 millitorr pressure. Al was used as mask material. The etching rate was 32 nm/min in the first 60 min. When the sample was etched for more than 60 min, a rate-inhibiting layer started to form. The micromasking effects and spikes were observed on the sample. In order to achieve a deep etch and a high quality etched surface for device fabrication, an electron cyclotron resonant (ECR) reactive ion etching system was employed using a CF₄ + O₂ gas mixture to etch 6H-SiC. A high etch rate of 80 nm/min which is independent of etching time and an excellent surface morphology were obtained in 6H-SiC sample with 650 W microwave power and 2 millitorr pressure. It is believed that high plasma density and low pressure in the ECR RIE system are important factors for this result. However, the durability of mask material is an important issue. A further study is underway to identify the optimal etching conditions and suitable etch mask materials using ECR RIE system.

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Table I Structure parameters of 6H-SiC Schottky diodes, p⁺n diodes and thyristors. All epilayers were grown on N-type 6H-SiC substrates with (0001) Si terminated surface.

sample	epilayer	conductivity type	doping level (1/cm ³)	thickness (μm)
Schottky	1	n	3.4×10^{15}	10
p ⁺ N	1	n	5.4×10^{15}	8
Thyristor	1	p	1×10^{17}	2
	2	n	5×10^{15}	6.5
	3	p ⁺	1.3×10^{19}	1.5

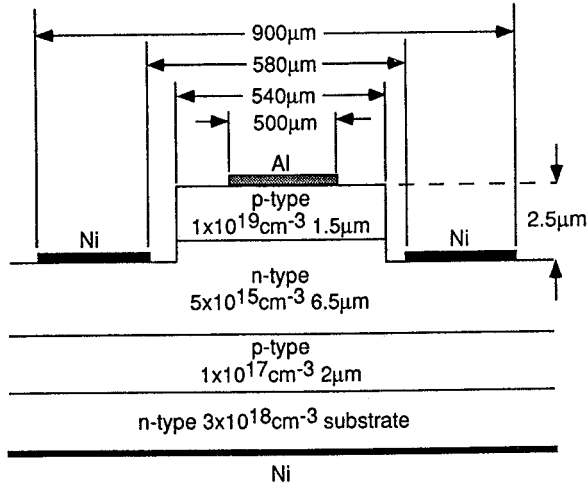


Fig.1 Schematic diagram of 6H-SiC thyristor cross sectional view

The p⁺n diodes were fabricated with a 600 μm diameter mesa dimension and a 500 μm diameter Al contact dot. The thyristor cross sectional view is illustrated in Fig. 1. with the dimensions indicated. Au or Pt Schottky contacts have a diameter of 400 μm diameter. For all the devices, Ni and Al were used to form ohmic contacts to n-type and p-type 6H-SiC regions, respectively. Contact sintering was done by rapid thermal annealing between 900 and 1000 °C.

III. Device Switching Characteristics

A. 6H-SiC Schottky Diodes

Schottky diodes were characterized by C-V and I-V measurements first. Au/6H-SiC diodes exhibit a barrier height of 1.06 eV from C-V measurements (0.96 eV from I-V data) and an ideality factor of 1.25. Pt/6H-SiC diodes show a barrier height of 1.19 from C-V measurements (1.01 from I-V data) and an ideality factor of 1.35. The barrier heights are in good agreement with other reports[7,11]. The switching characteristics were investigated using optical triggering. The trigger light source is a Nd:YAG laser with laser wavelength quadrupled from 1.06 μm to 266 nm. The laser energy is 1.7 mJ which is made up by 60 % of 266 nm laser line and 40 % 523 nm laser line. The laser pulse width is around 75 ps. The test circuit is a charged line pulser composed of a 50 ohm coaxial cable, switching device and 50 ohm load. The focused laser beam was shone on the front surface of Schottky diode contacts. The laser beam size is about 5 mm in diameter and is large enough to cover the metal contact and the surrounding edge region. The p⁺n diode was

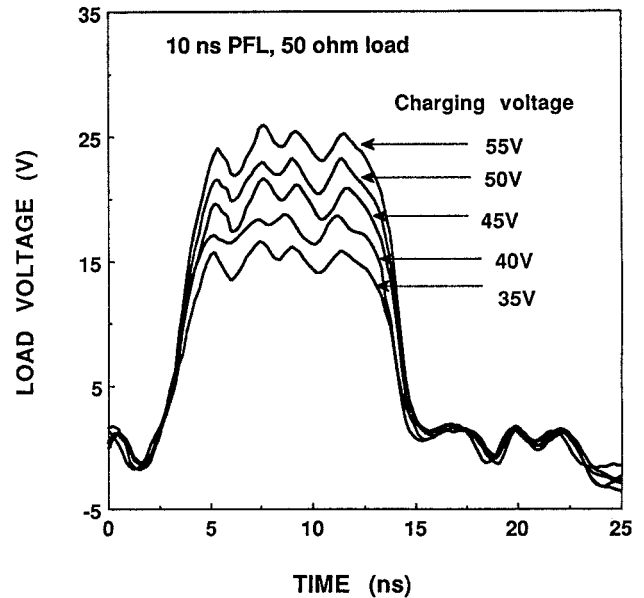


Fig.2 Voltage switching waveform of Pt/6H-SiC Schottky diode at various charging voltages using 266 nm laser triggering.

also illuminated in the same way. Fig.2 shows load voltage switching waveform at various charging voltages for a Pt/6H-SiC Schottky diode. A near 100% switching efficiency is obtained at various charging voltages. It is known from transmission line theory that the maximum switched voltage is 50% of charging voltage in this circuit when there is no on-state switch resistance[12]. The Au/6H-SiC diodes show the same switching characteristics. In order to test the spectral response of Schottky diodes, 266 nm laser line was blocked from the laser output. It is interesting to note that the Schottky diodes show a very weak response to 523 nm laser line. This is consistent with a report on spectral responsivity of 6H-SiC UV photodetectors which showed a maximum responsivity at 270 nm[9].

B. 6H-SiC P⁺N Diodes

The breakdown voltages of 6H-SiC p⁺n diodes are measured to be larger than 400 V. This corresponds to breakdown fields larger than 1×10^6 V/cm. It should be noted that the 6H-SiC p⁺n diodes fabricated for this study did not have any edge termination design or surface passivation to improve the reverse breakdown voltage. Minority carrier (hole) lifetime in n region is determined from reverse bias transient recovery time to be around 38 ns. An optical switching waveform triggered by 266 nm laser line is shown in Fig. 3. Two different reverse bias conditions were used in the optical switching measurements. One is pulsed reverse bias and one is constant DC reverse bias. Switching efficiencies for both 6H-SiC p⁺n diodes and Schottky diodes are plotted as a function of charging voltage in Fig.4. The relatively low switching efficiency in the p⁺n diode can be ascribed to the fact that photon absorption in and around the junction depletion region is less due to a high photon absorption in the 2

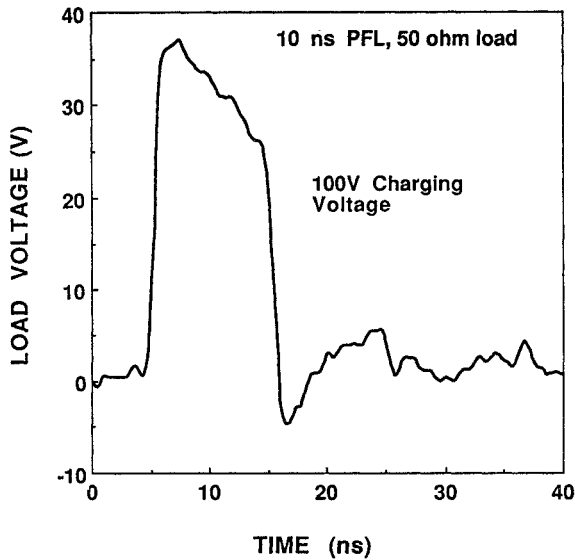


Fig.3 Voltage switching waveform of 6H-SiC p+n diode using 266 nm laser triggering.

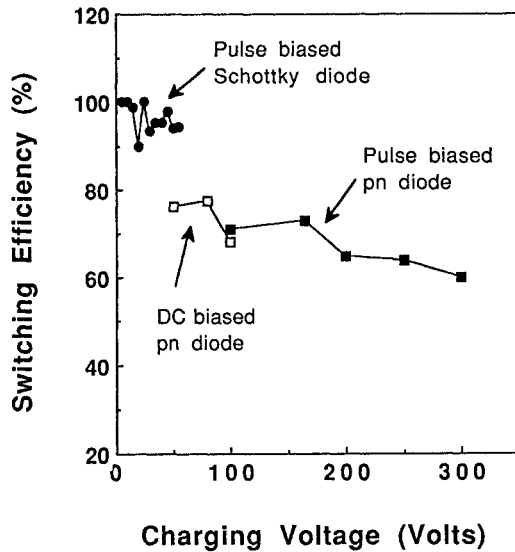


Fig.4 Switching efficiency as a function of charging voltage for both 6H-SiC p+n and Schottky diodes.

μm thick p^+ layer. In the case of Schottky diode, since the Schottky metal contact is only about 700 \AA in thickness, most of photon absorption occurred in the depletion region right under metal contact leading to a higher switching efficiency.

C. 6H-SiC Thyristors

6H-SiC thyristors were tested with electrical gating using a measurement circuit shown in Fig.5. Fig.6 shows 6H-SiC thyristor DC current-voltage characteristics. Because of the simple thyristor fabrication without deep mesa etching of the reversed base-collector junction, a low forward blocking voltage is not unexpected. From the expanded thyristor dynamic switching waveform shown in Fig. 7, a delay time of 240 ns is observed. The turn-on

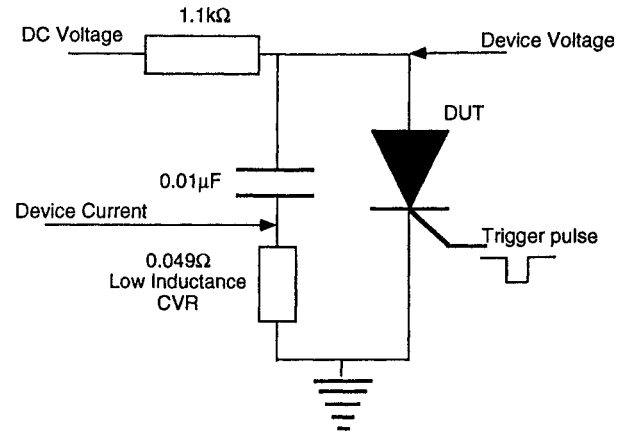


Fig.5 Measurement circuit for 6H-SiC thyristor switching characterization.

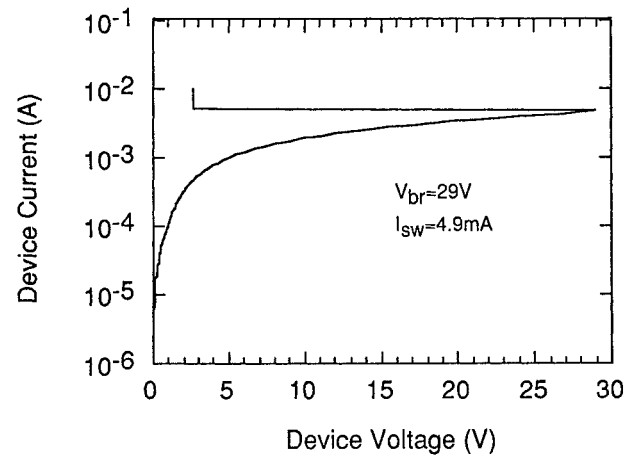


Fig.6 6H-SiC thyristor DC current-voltage characteristics.

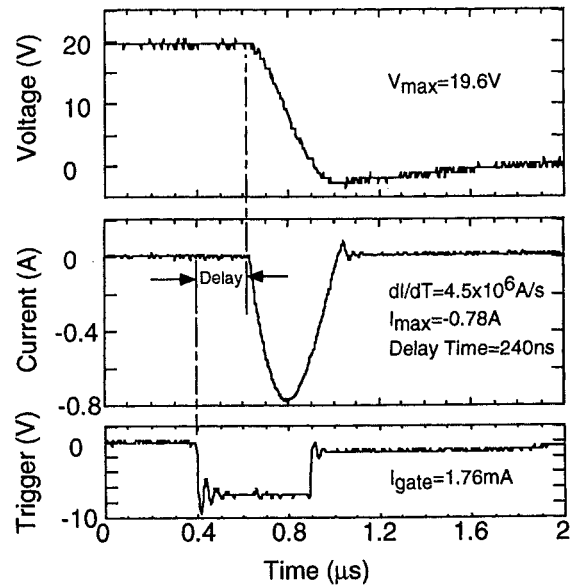


Fig.7 Dynamic switching characteristics of 6H-SiC thyristor.

time is about 170 ns. Based on a diffusion model [13], turn-on time is given by $(W_n^2/2D_p \times W_p^2/2D_n)^{1/2}$ and is calculated to be about 60 ns with D_n of 2.5 cm²/s and D_p of 0.25 cm²/s. The W_n and W_p are the n-type and p-type base region widths respectively. The much longer turn-on time observed in this study is not understood. However, the long n-type base region and relatively short carrier lifetime (~ 38 ns) may be responsible for the long turn-on time. Small forward hold on voltage is desired for less power consumption. This thyristor shows about 3 V forward hold-on voltage which is only slightly larger than the bandgap of 6H-SiC. Further fabrication and characterization are currently underway to realize high performance thyristors using deep dry etching techniques and the results will be reported elsewhere.

IV. Summary

6H-SiC switches, including Schottky diode, p⁺n diodes and thyristor have been fabricated using ECR reactive ion etching. High etching rate of 80 nm/min and excellent surface morphology were obtained in 6H-SiC samples. Schottky diodes and p⁺n diodes show high switching efficiency using 266 nm laser light for triggering. Functioning 6H-SiC thyristor has been demonstrated.

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